Project Description
An External Calibrator for HI Observatories

1. Summary

A new generation of radio arrays is being developed that use large numbers of low-cost elements, such as phased tiles of dipole antennas. This is made possible by developments in digital technology and enables exploration of new windows on the universe such as the epoch of reionization (EoR) via the redshifted 21 cm line (Morales & Wyithe 2010; Madau et al. 1997; Loeb & Zaldarriaga 2004; Loeb & Barkana 2001; Furlanetto et al. 2006). Precise calibration of the primary beams of these dipole arrays has been found to be crucial to analysis of observations from the the Murchison Widefield Array (MWA; Tingay et al. (2013); Bowman et al. (2013)), the Precision Array for Probing the Epoch of Reionization (PAPER; Pober et al. (2013); Parsons et al. (2010); Jacobs et al. (2011)), and the Low Frequency Array (LOFAR; Yatawatta et al. (2013)). Beam calibration of low frequency dipole arrays poses several complications compared to traditional dish antennas. Most notable is that holographic beam calibration is not possible because the dipole array beams are steered electronically and are unique at every pointing direction. Drift scan calibration of dipole array beams is possible, but requires the test antenna/array to be embedded within an existing array that generates sufficient sensitivity to isolate a large number of radio sources to provide many tracks through the beam. Pober et al. (2012) have employed symmetry arguments to reduce the needed number of sources on the sky and improve the result for PAPER antennas, but this is not possible in general for more complicated dipole array beam patterns. Attempts have been made to use anechoic chambers to calibrate low-frequency phased arrays, but the measurements suffer since even the largest chambers cannot extend into the farfield pattern and the RF absorber material used in the chambers performs poorly below 150 MHz, creating reflections and resonances. Mapping of the dipole beams using the Orbcomm constellation of satellites has proven effective (Neben, Bradley and Hewitt in prep) but is limited to only a single frequency (138 MHz).

The work proposed here will develop a method for directly measuring, in-situ, the response of dipoles, phased array tiles, and other experimental low-frequency receptors, particularly new elements proposed for the second generation Hydrogen Epoch of Reionization Array (HERA). The proposed method use a remotely controlled unmanned aerial vehicle equipped with a calibrated transmitting antenna and GPS and inertial position loggers to provide a known mulit-frequency reference signal for calibrating low-frequency antennas. Substantial initial development work has been performed already to design and characterize a prototype system. Here, we request modest funds ($99,187 over two years) to support the implementation of a mature, deployable system based on our prototype efforts. A team of undergraduates, led by one postdoc (0.1 FTE), will assemble and field the prototype in a series of field experiments with the goal of routinely mapping the primary beams of several low frequency arrays, including the HERA prototype antenna installation outside Berkeley, CA.

2. Science Background: 21 cm Epoch of Reionization[1]

The science enabled by large radio arrays includes the discovery of previously unknown objects, probing large scale structure, and imaging the universe during its first billion year. The current focus of low frequency phased arrays is on opening a new window on the early universe during the epoch of reionization, when the influence of early stars, galaxies, and black holes grew substantial enough to drive the last global phase transition, the ionization of atomic hydrogen (HI) in the intergalactic medium, thought to occur at redshifts $z > 6$. Exploration of the Cosmic Dawn, including the reionization epoch and era of First Light, has been called out as a top-level priority by the Astro 2010 decadal survey.

Above redshift $z > 6$, as the IGM becomes increasingly neutral, HI is visible in 21 cm radio (1421MHz), redshifted into the 100-200 MHz band. The hyperfine line is very narrow and thus an excellent tracer of redshift, giving relative distance at fine tunings and cosmological time at coarse. The 21 cm line is faint, a 10 mK signal on top of 100K foregrounds, but is highly spectrally variable compared with synchrotron foregounds, and thus distinguishable with appropriate filters. The HI emission traces out the matter distribution on scales of 1-100Mpc, and via contrast the HII regions carved by rapidly assembling stellar and black hole populations. At low sensitivities the power spectrum of HI emission, computed in three dimensions (2 spatial and 1 spectral), constrains the timing of reionization and the emission, absorption, and mass properties of early galaxies. Full spectral cube imaging provides all of this information in a fully three dimensional geographic context which will be key to routine redshift 8 astronomy with James Webb Space Telescope and future large ground-based observatories.

There are several, purpose built, 21cm EoR low frequency telescopes either finishing construction, or beginning observation, most notably Low Frequency Array (LOFAR) in Europe, Precision Array for Probing the Epoch of Reionization (PAPER) in South Africa and Murchison Widefield Array (MWA) in Australia. These telescopes are targeting a detection of HI during the Epoch of Reionization and are precursors to much larger arrays capable of detailed measurements including the second generation Hydrogen Epoch of Reionization Array (HERA) and the Square Kilometer Array (SKA).

PAPER and the MWA are now complete (see Fig. 1) and recording observations targeting a statistical detection of HI in the power spectrum domain and opening this new observing window with a modest array of 128 stations. The principle challenge is in making high sensitivity measurements in the presence of the bright foregrounds. Recent work (Pober et al. 2013; Parsons et al. 2012, 2013; Vedantham et al. 2012; Morales et al. 2012; Bowman et al. 2009; Datta et al. 2010; Liu & Tegmark 2011) has shown that the reionization signal is separable from smooth foregrounds in the 3D power spectrum domain and that with increasing instrumental precision more foregrounds can be removed revealing the brightest EoR modes.

[1]This proposal and the EoRLive proposal by Jacobs share portions of text since both are motivated by the same science goal to improve the return from MWA, PAPER, and upcoming reionization instruments. The two proposals are independent and each addresses a unique aspect of instrument performance (data quality and organization and here, primary beam calibration with ECHO) that has been identified as a high priority by recent operational experience from the telescopes.

Fig. 1.— PAPER (left) currently observing at the SKA-South Africa site, has placed the tightest constraints on HI $z > 7$ and the MWA (right) currently observing at the SKA-Western Australia site is forecast to have the sensitivity to make even tighter constraints.

3. Challenge Addressed Here: Precision widefield calibration of fixed dipoles

Probing the Epoch of Reionization with HI at low frequencies is directly enabled by the steady improvement of modern digital electronics which are now able to sample and correlate hundreds of antennae in the MHz band, dramatically lowering the digital cost per antenna. One dish might be replaced with dozens of dipole arrays at a significant increase in collecting area. This has driven the design of the MWA, PAPER, CHIME , LOFAR, LWA , HERA and the Square Kilometer Array (SKA). All use fixed dipoles as primary elements and have fields of view tens of degrees wide.

One of the biggest contributors to EoR foreground contamination is the wide field of view and imprecise primary beam model. The response of the PAPER dipole elements is quite broad on the sky and slowly decreases in amplitude towards the horizon, while the MWA phased array tiles of dipoles is characterized by an approximately 30-degree primary lobe bordered by nulls and, at some frequencies, far-out sidelobes. In both cases, sources far off axis enter with very high chromatic aberration and spectral phase ramps, all of which leak into the EoR modes of the 3D power spectrum. This situation is summarized in Figure 5, which demonstrates this effect in recent MWA data. In this case power from the galaxy is the chief contaminate. A second effect arises when the data from multiple antennae are combined. Small differences between antenna beam patterns, arising due to manufacturing and installation tolerances or temperature differences, can lead to large power spectrum errors (Morales et al. 2012).

Precise knowledge of the primary beam will allow forward modeling and removal of these components. Algorithmic development (Bhatnagar et al 2008, Sullivan et al 2012) has paved the way for the use of these models, however actual measurement of beam patterns (for both MWA and PAPER) has lagged behind. The measurement of the primary beam is simple in principle: map the apparent amplitude of a known transmitter as it moves through the beam response. Given the way the beam enters into the EoR observation, the desired characteristics of the measurement are: 1) fully map the beam to the horizon 2) cover the full spectral band of the instrument 3) work in the far-field with the transmitter many wavelengths away, 4) acquire in-situ measurements since the environment influences low-frequency antennas, and 5) achieve precision of better than 1Several experiments have worked to measure the primary beam, a summary of which but none meet all of these criteria. They are summarized in Table 1

Simulation:
The majority of the data reduction being done for PAPER and MWA is currently employing some kind of simulation (analytical or finite difference) to correct the effect of the primary beam. These have been shown to be in disagreement, both with each other and with reality at the 10-50% level (Jacobs et al. 2013). See Figure 4 for a comparison between models and an estimate of the flux error comparing MWA fields.

Anechoic chamber:
An anechoic chamber is a large room with walls that damp reflections to simulate free space. Testing of an MWA tile was done in a large chamber at Lincoln Labs (see Figure 2). This test provided the first experimental measurement of the phased array beam pattern, and helped refine the spectral response of the bow-tie dipole. However the room is not suitable for frequencies below 150MHz as the wavelength size of 2m approaches the size of the room and begins to violate the far field requirement. Thus though very high precision is possible, the accuracy of the measurement is distorted.

Satellite:
The Orbcomm satellite constellation of 29 low earth orbit satellites has a downlink transmitter at 137MHz that has been used to map the primary beam. Though they are in the far field, the digital transmissions make stable measurements difficult. Using all satellites in the constellation the beam coverage is complete to 80%, leaving a large gap in the north (See figure 3). The limitation to 137MHz is also problematic because it is far from the primary EoR band at 150-200MHz and the beam models are known to be worse at higher frequencies. Bradley (NRAO) and Hewitt (MIT/Kavli) have built a system that measures the incoming Orbcomm signal relative to a calibration standard dipole, example maps are shown in Figure 3. This system is currently being used at the NRAO site in Green Bank, WV to map the MWA phased array beam. The Orbcomm satellites pass, on different tracks, several times a day. The principle limitation to this work is that each change in the instrument must be followed by several days of observing to build up enough satellite passes to cover the beam. Experimentation proceeds slowly but the system is now producing its first maps (see Figure 3).

Extra-galactic sources:
Given a high quality catalog of point sources, a set of perceived fluxes as measured by the instrument in question might be used to map the beam. This has been attempted, for PAPER by Pober et al 2011, with mixed results. Uncertainty in the catalog requires leaving source fluxes as free parameters, however because each source track through the beam never crosses any other source track, 180d rotational symmetry of the beam must be invoked. This assumption is violated by the MWA. In practice this method is not on the same plane as others because it does not introduce any new information, while providing confirmation of other methods, without external information it does not reach the required precision.

4. External Calibrator for HI Observatories (ECHO)

ECHO is a fully contained calibration source designed to provide high precision measurements of the beam pattern of fixed dipole arrays. An automated small unmanned aerial vehicle (known to enthusiasts as an octocopter) carries a transmitter and antenna over the array, providing a high quality calibration source under direct control by the experimenter. The transmitter uses a very stable voltage controlled oscillator to generate many continuous wave signals which are input to a wide-band antenna. The antenna under test and supporting receiver system can be in a variety of configurations either as-built in the array or set up in a test configuration with a spectrometer or an absolutely calibrated dipole standard. The octocopter was selected because of its high degree of stability, lift capability, and precision avionics which give it the capability to follow preprogrammed GPS paths.

The ECHO is system is technically challenging due to the need for 1) a broadband transmitting antenna that works across the 1 to 3 meter bands, but is small and light enough to be lifted, 2) accounting for the beam pattern of that antenna, 3) transmitting a stable signal, and 4) developing a robust experimental technique that is easily deployed to test sites around the world. We have overcome these inherent challenges in our fully functional prototype, ECHO1.

Work to date has included acquiring (in partnership with the MWA) an Octocopter drone (see Figure 6), selection and mounting of an antenna, detailed electromagnetic simulations of the configuration, selection and test of a transmitter, and flight tests (Figure 7). The finite element simulations (see Figure 6) have shown that the basic metallic components of the drone provide a small amount forward gain but induce little asymmetry, a product of the eightfold arm symmetry. The selected antenna was chosen for its smooth spectral response as well as its small size and weight. The antenna impedance was measured both in the lab and in the labs rooftop Free Space Simulator where antenna responses can be measured with minimal distortion from nearby parasitic elements and was found to have a very flat spectral response. After testing several possible transmitters a computer controlled Voltage Controlled Oscillator (VCO) was chosen. The VCO is tunable, by computer command, to any frequency between 125 and 2GHz. The original application of the VCO is as a clock standard for MHz analog to digital samplers and is highly stable in phase and amplitude, yet delivers enough power to reach a range of hundreds of meters.

The antenna is mounted to the drone by custom 3D printed parts designed by an engineering systems student. The entire package (transmitter, antenna, hardware) weighs 0.9 kg. At this weight, ECHO1 has a flight time of 15 minutes, during which it may perform several scanning patterns. Flight tests to date (see Figure 7) have focused on measuring the stability and repeatability of commanded flight patterns as well as the stability of the received signal. The position hold is stable to 2m rms lateral motion and 0.5m vertical. At a flight ceiling of 100m, this amounts to $\sim 1^{\circ}$of apparent motion, well within the acceptable bounds for most beams which vary on 5-10°scales. Circular flight (i.e. tracing out beam contours) was also tested and with suitably low speeds is repeatable at this same level of precision. The signal is highly stable (Figure 7) to with no drift detectable within the precision of these first measurements.

4.1. Proposed Work

Our goal is to enable routine, high precision, mapping of wide-field dipole arrays. The funding requested here will support a small team of undergraduates to deploy our existing prototype system to map beams of several antennae. Using this data we will characterize the error and make changes in hardware or method reduce the error until it is within acceptable bounds. In the first year we will see the first beam maps of individual MWA and PAPER dipoles, as well as an experimental HERA dish, now under construction at a ranch outside of Berkeley, CA. Based on these results, we will implement a second-generation system suitable for use by the entire community to characterize existing arrays and aid in the development of future antennas. At the end of the this project, we will make the resulting ECHO system available on a best-effort basis to any interested user, as well as seek opportunities to actively contribute to HERA and future low-frequency array design efforts.

The first beam maps produced by ECHO for MWA antenna tiles will be incorporated into imaging analysis by the UW MWA imaging team which uses an imaging package based on Fast Holographic Deconvolution (FHD). FHD is an efficient imaging algorithm that accounts for the response of the antenna beam. Another full-imaging deconvolution employs forward modeling (Bernardi et al. 2011; Pindor et al. 2011) developed imaging routines for the MWA, which are currently being applied to image both MWA and PAPER data. These efforts will incorporate the improved ECHO beam models as they become available (private communication, G. Bernardi).

In the second year we will build ECHO2, which will incorporate the refinements and features resulting from the prototype trials. Octocopter UAV technology continues to improve significantly each year while costs plummet. The drone currently in use cost $8000 at the time of its purchase, but a similar drone today costs $1000 and is significantly more capable in both platform stability and autonomous navigation, both of which are important for absolute beam calibration accuracy.

ECHO2 will be able to support the in-situ measurement of as-built arrays like PAPER and the MWA. The design emphasis will be on providing simple, routine deployment as a contribution to collaborative telescope construction and operation. The PIs are senior members of MWA, PAPER and HERA. Use of ECHO is targeted to aid in refining design by the HERA roadmap by 2015. The two-year program proposed here addresses that goal, but is not dependent on HERA for testing and deployment scenarios.

4.2. Timeline, Resources and Management Plan

This proposal seeks funds for a two student team of undergraduates to field test the now complete ECHO1 and to implement ECHO2. They will be advised and assisted by ASU postdoc Dr. Daniel Jacobs.

The ASU low frequency cosmology group has had good success building teams of students that target software and hardware development, including implementing a 500W solar power system for EDGES and currently in use at OVRO, an automated MWA beamformera calibration switch network, one Small Radio Telescope (SRT) and two Very Small Radio Telescopes (VSRTs), an iPhone app for outreach based on the Dr. C animated pedagogical agent (http://mars.jpl.nasa.gov/drc/), and the ECHO1 prototype system, which is the work of three students (2 Physics, 1 Exploration Systems). There are approximately five students employed by the lab at any one time, many of whom are also supported by NASA Space Grant internships.

Prof. Judd Bowman (ASU, PI) will advise students and postdoc-PI and help provide overall direction. He is an assistant professor of astrophysics in the School of Earth and Space Exploration at ASU. He has a long-standing interest in questions that require analysis of large datasets. Prof. Bowman is Project Scientist of the Murchison Widefield Array radio telescope (Bowman et al. 2013, Tingay et al. 2013). He is the recipient of a NASA Nancy Grace Roman Early-Career Technology Fellowship to develop low-frequency, wideband radio technology applicable to cosmology, space exploration, and earth-monitoring missions. He is a Co-I on the HERA team. Prof. Bowman developed software resulting in two NASA Software Release Awards (2004, 2005), produced the Mars Exploration Rovers Screensaver distributed by NASA to over 100,000 users (2004), and architected algorithms for JPL's *Dr. C* animated pedagogical agent (http://mars.jpl.nasa.gov/drc/).

Results from previous support: Prof. Bowman is PI of two NSF collaborative research grants: AST-1109257 to identify optimal statistical techniques for analyzing new cosmological observations, and AST-1109865 to develop techniques for improving the processing of large systems of radio astronomy antennas. He is PI of the EDGES astrophysics experiment (AST-0905990, 9/1/09-8/31/13, $392,446 and AST-1207761, 6/1/12-5/31/15, $842,117). **Intellectual merits:** The EDGES experiment aimed to design and build a high-precision low-frequency (100 to 200 MHz) radio spectrometer in order to place the first constraints on the hydrogen reionization history of the universe between $6 < z < 15$ through the cosmological redshifted 21 cm emission signature. EDGES achieved all of its objectives and, in 2010, yielded the first constraints on reionization from any radio experiment using the 21 cm signal, published in *Nature* (Bowman & Rogers 2010b). The system draws on the findings of preliminary investigations (Bowman et al. 2008; Rogers & Bowman 2008). The detailed documentation of the instrument development and characterization process are publicly available in the online memoranda (`http://www.haystack.mit.edu/ast/arrays/edges`, `http://loco.lab.asu.edu/memos`). **Broader impacts**: EDGES was deployed to characterize the radio frequency interference at several geographically remote areas in the U.S. and Australia (Bowman & Rogers 2010a) and it led to a new formulation of an extended noise wave propagation model for accurately calibrating a broadband, mismatched radio receiver with lossy transmission (Rogers & Bowman 2012). As part of these projects, the ASU group conducted and supported several education and public outreach events to reach both traditional and underserved audiences in the Phoenix metropolitan area and southwest region. These include: classroom visits and activities reach 65 elementary and middle school students and three teachers; on-site student visits; and participation in two large events at ASU that reached over 13,000 visitors. Undergraduate and graduate students presented ongoing research in EDGES and radio astronomy, engaging the public inside and outside by demonstrating a spectral analyzer powered by a solar panel and showing FM, TV, and cell phone signals. Kids of all ages interacted, learning about the electromagnetic spectrum and viewing the US Radio Frequency Allocation Chart, and the importance of 'Radio Quiet" zones. They became "RFI Detectives" using a transistor radio to search for and list sources of RFI in the building (adapted from the NRAO RFI Detectives activity).

Dr. Daniel Jacobs (ASU, Co-PI) will advise and assist on all aspects of the ECHO1 and ECHO2 test deployments and fabrication. He has over a decade of experience in low frequency radio astronomy with MWA and PAPER. As PI of the Montana State University Cubesat program he led a team of undergraduates in their effort to construct and launch the E1P satellite, the first Cubesat to successfully qualify and launch under the NASA Educational Cubesat launch program.

Dr. Jacobs is a central member of both the PAPER project (NSF #1129258) and the MWA; leader of precision calibration for PAPER; author of the first EoR foreground catalog (Jacobs et al 2011), detailed error analysis (Jacobs et al 2013a) and a precision calibrator observation which sets the flux scale for future EoR efforts in the southern hemisphere (Jacobs et al 2013b); co-architect of the PAPER power spectrum approach which currently provides the best foreground isolation and deepest EoR integration. His contributions to the MWA include development of commissioning calibration pipeline and leadership of an international team of collaborators from MIT, U. Melbourne, UW, U. Sydney, ANU, Raman Research Institute to complete the first EoR observing campaign and organize the results in the MIT EoR Archive (NSF #082132).

Two ASU undergraduates will be responsible for day-to-day implementation and test activities. This will include ECHO1 field tests, reduction and publication of the results of these tests; design and construction of ECHO2; and at least one deployment for in-situ beam mapping of MWA and PAPER at Green Bank and (subject to funding) the South Africa HERA site.

Prof. Rich Bradley (UVA/NRAO, collaborator) is an expert in radio instrumentation, co-PI of the PAPER project, and co-I of the proposed HERA.

The senior members of the project team account for a significant fraction of the US EoR community and active observing and data analysis programs. Relevant hardware and data access will be available as necessary and beam measurements will be rapidly disseminated among the EoR community.

- **Summer 2014** Field testing ASU, choose optimal flight plan, make first beam maps,
- **Fall/Winter 2014** Refine transmit, receive loops to reduce errors. Begin ECHO2 design and build. Incorporate first beam maps into imaging with FHD. Publication of method paper.
- **Summer 2015** Field deployments of ECHO2, incorporation of very high precision beam maps. Students present work at Winter URSI Radio Science Meeting

4.3. Flight Safety and Regulations

Current FAA guidelines class the ECHO drone in the smallest hobby classification. These guidelines require positive control and suggest a flight ceiling of 400 feet, both of which ECHO is within. Preliminary approval has been obtained from NRAO, via collaborator Dr. Rich Bradley, for flight and transmitter use at the NRAO Green Bank facility. Flight safety (both of the craft and surroundings) is a principle focus of operation. Practices such as use of redundant controls, weight limits, and judicious choice of flight times and locations are all made with a view towards safety.

5. Broader Impacts

The ECHO project will aid in training and recruiting undergraduates with interests in electronics and field experiments into a rapidly growing field of astronomy, while providing scaffolded mentoring in STEM education. The ASU Low frequency Cosmology lab specializes in recruiting, training, and mentoring undergraduates for hands on projects with students working on several projects at any one time including the Experiment to Detect the Global Epoch of Reionization Signal (EDGES), the proposed Dark Ages Radio Explorer (DARE) mission, and several student initiated projects including a Very Small Radio Telescope (VSRT) station. ECHO is currently staffed by undergraduates who are majoring in physics, astronomy, and mechanical engineering, and space systems design. Students have tested, designed, and built the transmitter payload and integrated it into the drone as a functional subsystem. The students are responsible for flying the current experimental missions and, under this project, will travel to telescope sites for in-situ calibration. The helicopter drone system is popular with the public and is featured prominently at outreach events, including at the monthly Earth and Space Open House (500 visitors/month), ASUs annual Earth and Space Exploration Day (3000 visitors), ASUs annual Night of the Open Door (10,000 visitors), and at the Arizona Science Center. The project will also be included in regular visits to local elementary schools, including to the Salt River-Pima Maricopa Indian Community Schools, where it will help to engage young students in the diverse Phoenix metropolitan area.

ASU is one of the countrys leading minority enrollment institutions and producers of STEM graduates. In 2010, it had 30% minority enrollment and it ranked #1 in PhDs for American Indians and #5 for Hispanics. ASU has been recognized as one of the top five universities in the nation for corporate recruitment (http://www.asu.edu/excellence/excel/). This project will establish a lasting foundation to prepare students to provide key roles in STEM careers technology development. This is especially pertinent on a regional level, the state of Arizona currently has no other undergraduate program that directly trains future scientists and engineers to work together to achieve national space objectives, nor any institution that serves to combine space science-related and engineering curricula into a single program.

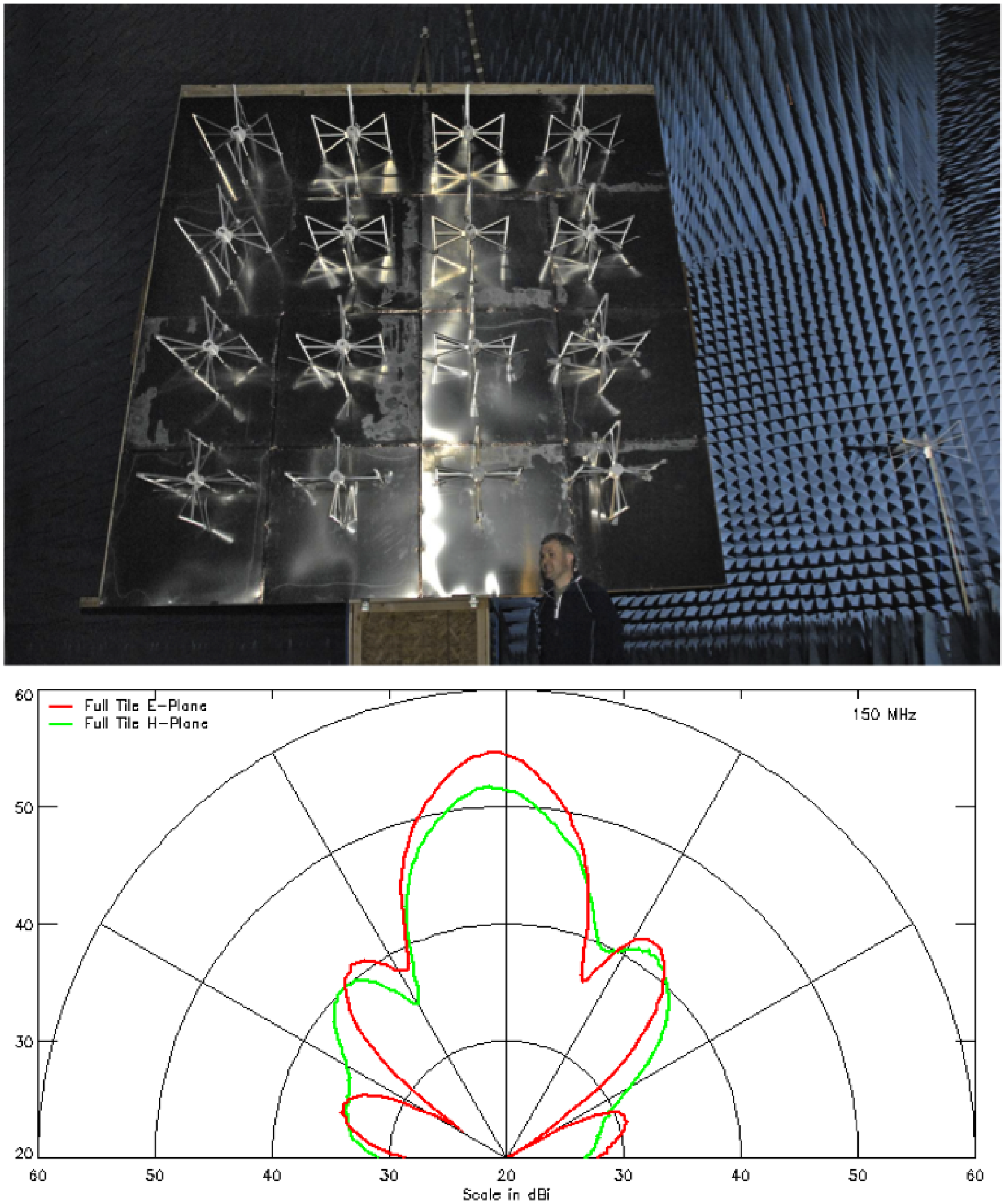

Fig. 2.— Top:An MWA tile undergoing beam mapping in an en-echoic chamber at MIT-Lincoln Labs, the transmitting antenna source can be seen at right. These measurements provided key testing data during the tile design process but are impractical for characterizing the full array. An-echoic chambers at low frequencies face a number of experimental challenges such as operating at or below the low frequency limit of the chamber and with the transmitter in the near field where different electromagnetic assumptions obtain. Bottom: the resulting beam pattern. Note the slight asymmetry, though to be due to near-field effects.

Fig. 3.— Left: A beam map using the Orbcomm satellite network to trace out the grating lobes of the 4x4 antenna array compared with a dipole standard (Neben in prep). The primary limitation is that the satellites operate at 137MHz while the primary EoR band is 140 to 200MHz and anechoic chamber measurements are at 200MHz. Other drawbacks include the noise introduced by the digital transmission (note outlier tracks which are thought to occur during downlinks), the multi-day integration times required to fill in the coverage which limits the number of field experiments and the lack of high latitude coverage. The ECHO2 system will be able to provide maps of similar or better quality at 1 MHz intervals through the test antennas bandwidth. Right: The Orbcomm measurement test setup in Green Bank currently includes this MWA tile, a 32 station PAPER array, and a high precision reference dipole.

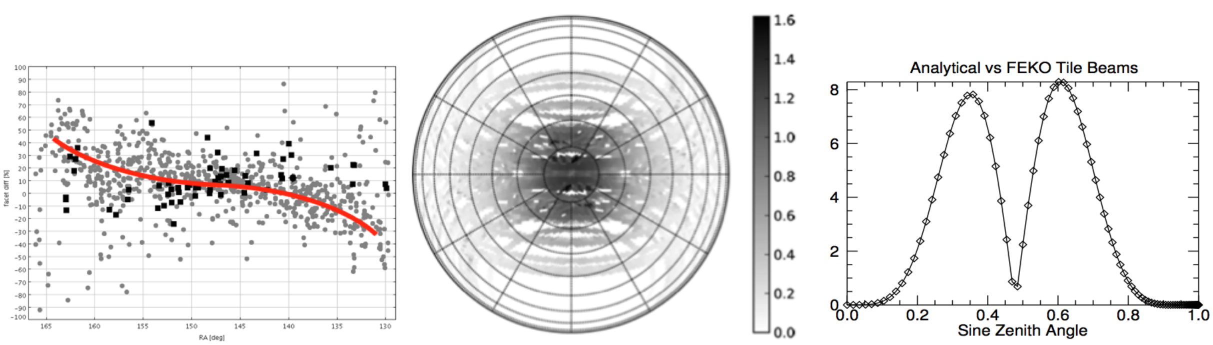

Fig. 4.— Evidence for primary beam uncertainty. Left: Fractional flux difference between different pointings in the MWA survey by Williams et al. (2012) plotted vs right ascension reveals a systematic characteristic of an error in the beam model (Jacobs et al. 2013). Center: Measurement of the PAPER primary beam using sky sources as they drift through the beam (Pober et al. 2012). Because the calibrators are locked to the sky the result is fundamentally limited to beams with 180d rotational symmetry. Right: Percent difference between two MWA tile simulations, indicating the scale of simulation uncertainty. Typical errors range from 1 to 10% depending on tile pointing and frequency. (MWA Memo; McKinley B., 2012)

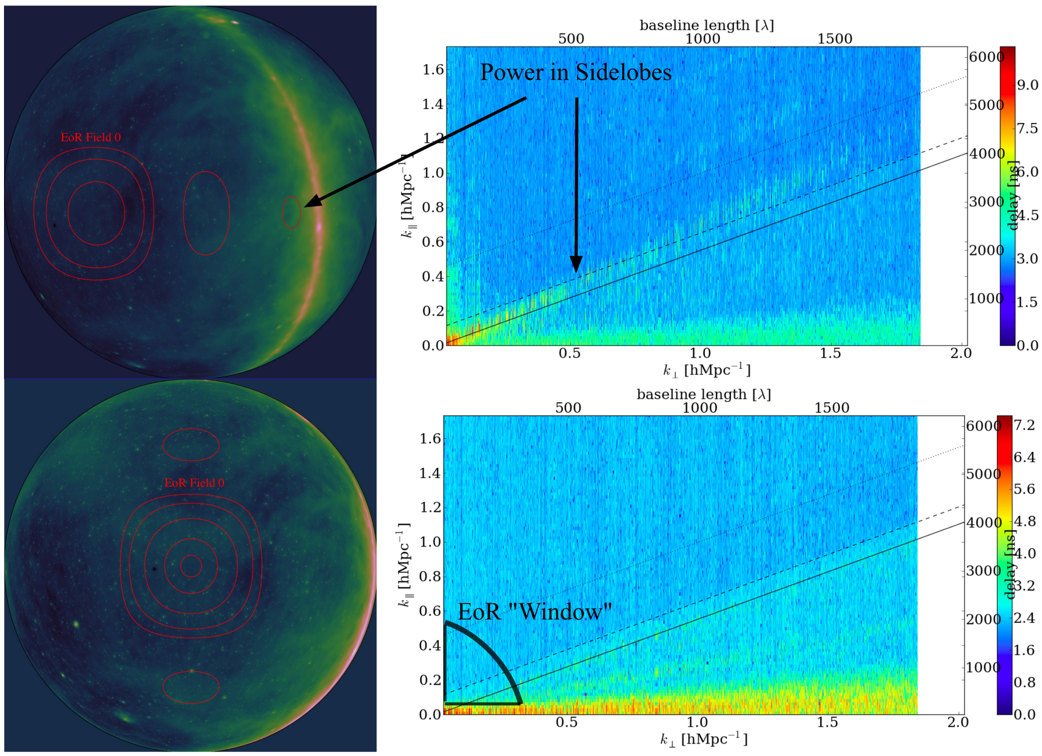

Fig. 5.— Left: Recently recorded MWA power spectra (right) and corresponding primary beam coverage (left). The principle features of the power spectrum are the linear increase in foreground contamination (expected levels indicated by the black line) and the EoR Window region where the signal will be strongest. The detection of HI in the power spectrum is limited primarily by foregrounds. Foregrounds far from the phase center, entering via the primary beam sidelobes, have higher spectral phase slopes, and therefore contaminate more $k_{\|}$ modes.

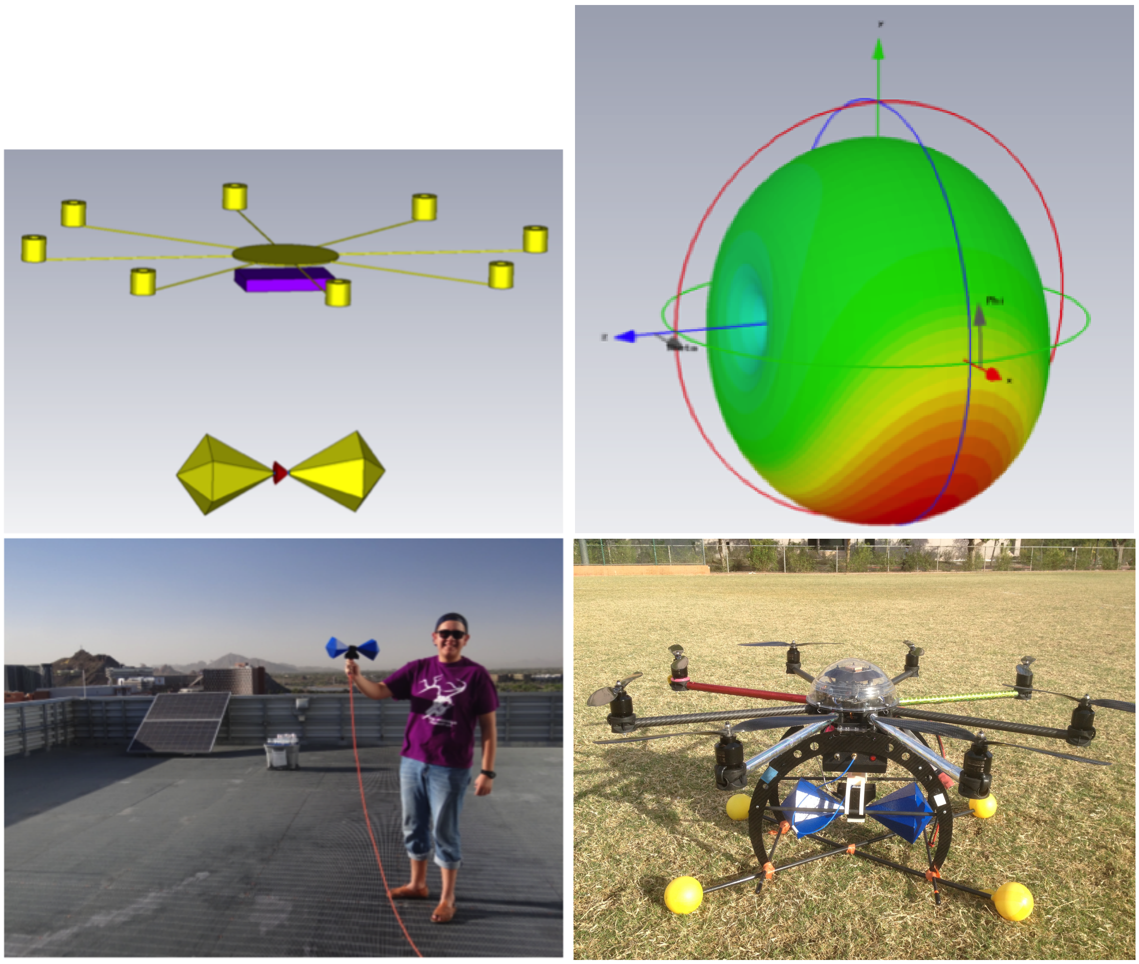

Fig. 6.— Examples of ASU undergraduate work to date on the ECHO1 prototype system. Top left: Finite element electromagnetic model including drone motors, wires and transmitter antenna with the resulting beam pattern shown at top right. Bottom left: undergraduate Jos Chavez measures the free space electrical impedance of the transmitter antenna. Bottom right: The complete ECHO1 prototype

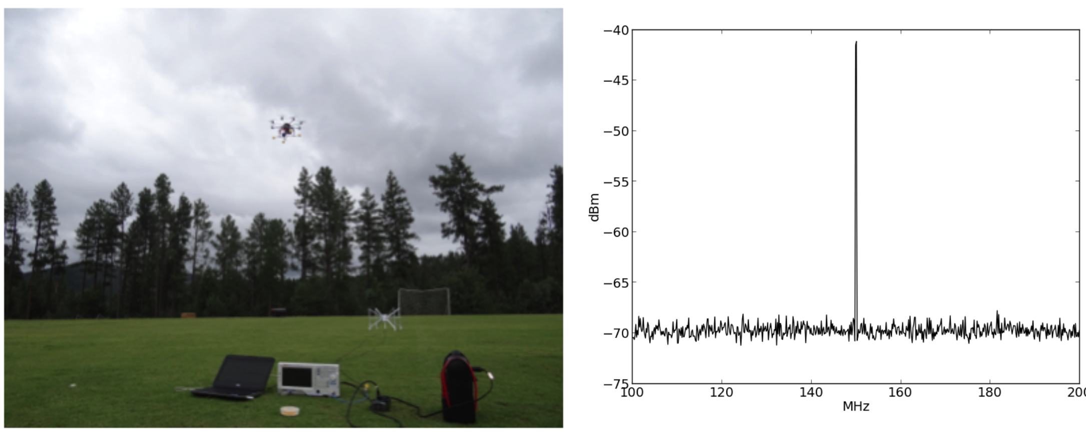

Fig. 7.— The first end-to-end flight test of the functional prototype, conducted by ASU undergrads David Nelson and Michael Busch, at an ASU summer camp two hours drive from Phoenix, where the FM radio background is low enough to make sensitive measurements across the spectrum. Left: ECHO1 in flight above the MWA tile under test. Right: Received spectrum demonstrating ideal signal to noise in the radio quiet mountainous terrain.